(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 January 2004 (15.01.2004)

PCT

(10) International Publication Number
WO 2004/005985 A1

(51) International Patent Classification[7]: G02B 6/12, H01L 33/00

(21) International Application Number: PCT/GB2003/002912

(22) International Filing Date: 7 July 2003 (07.07.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0215669.3 5 July 2002 (05.07.2002) GB

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(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),

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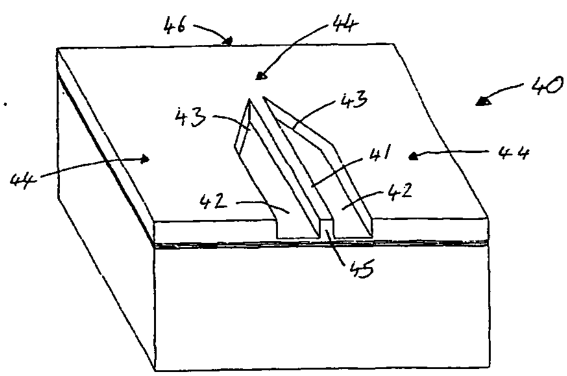
(54) Title: A SUPERLUMINESCENT DIODE



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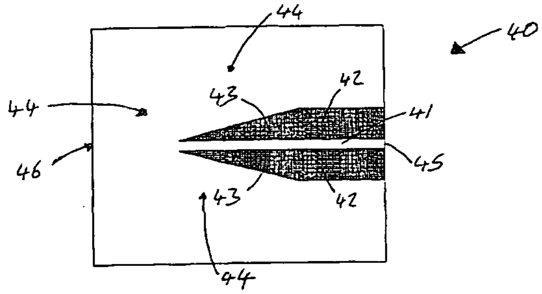

(b)

(57) Abstract: There is provided a superluminescent diode (SLD) comprising a planar optical waveguide (41) having two trenches (42) which extend from a facet (45) of the planar optical waveguide, the two trenches defining a ridge therebetween in the planar optical waveguide. At least one trench has at least a region (43) which is tapered, in which the width of the trench decreases with distance from the facet measured along the length of the trench. The tapering trench or trenches provide for light that is propagating away from the facet and guided by the ridge to be gradually evanescently coupled out to a surrounding broad area waveguide, thus reducing the amount of light that may reach a further facet and be reflected back into the guided mode.

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European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

A SUPERLUMINESCENT DIODE

Field of the Invention

The present invention relates to a superluminescent diode and in particular to a structure for reducing unwanted reflections within the diode.

Background to the Invention

The high power superluminescent diode (SLD) is widely used as a light source in optical sensors, gyroscopes, dense wavelength division multiplexing (DWDM) measurement systems and other types of optical system. The main requirements of SLD are high power, wide spectral width and low spectral modulation. In order to achieve these characteristics, the reflectivity of the end facets must be reduced to about 10^{-5} (0.001%) or less to suppress lasing oscillation under high power operation and to about 10^{-6} (0.0001%) to achieve low spectral modulation.

A number of techniques have been reported for reducing facet reflectivity. The most common techniques are antireflection coatings, tilting the stripe of the active region relative to the facet and window facet structures. It is difficult to achieve consistently low reflectivity, especially below 10^{-6}, at the end facets for a given output wavelength and even a slight temperature change that alters the output wavelength will change the reflectivity. Therefore, for a low facet reflectivity of 10^{-5} and below, a combination of several techniques is required. Some of the prior art concerning the applications of these techniques to the SLD are as follows.

One prior art technique employs a non-excitation absorption type SLD. By having a region to which no electrical bias is applied, the material becomes absorbing to the optical light generated in the active region. Light directed away from the output facet is therefore absorbed and the amount of light reflected back to the stripe is greatly reduced. However, under high power output operation, the intensity of the light generated in the active region due to the light-emission and recombination of carriers is increased and the ratio of the light reflected by the end facet and amplified in the active region is increased. In addition, there is a sharp refractive index change at the interface between the gain and absorption sections, and hence residual back reflection exists. Consequently, the light would not be sufficiently absorbed in the absorption region, resulting in laser oscillation.

SLDs which employ a combination of a straight portion and a bend portion have been fabricated and investigated. An SLD of this type may employ a waveguide that bends such that, at the facet, the waveguide is at an angle with a low associated reflectivity. Unfortunately, the waveguide, extending up to the facet, would enable the residual reflected field to be guided back along the stripe. In addition, as the light output direction is not perpendicular to the end facet, the efficiency with which the output light can be coupled to an optical fiber is not high.

U.S. Patent 4901123 discloses a technique, whereby a bend waveguide with a tapered end is used to suppress the lasing oscillation. The structure disclosed is based on a buried heterostructure stripe. Here, the tapering of the waveguide is strictly needed in order to avoid reflection at the interface between the end of the stripe and the window region. However, due to the limitations of lithography, it is difficult to obtain the very sharp end to the waveguide needed to attain very low effective reflectivity.

Summary of the Invention

According to a first aspect of the present invention an optical device comprises a planar optical waveguide having two trenches which extend from a facet of the planar optical waveguide, the two trenches defining a ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

The tapering trench or trenches provide for a gradual evanescent coupling out of the ridge of light propagating away from the facet, thus reducing the amount of light that may reach a further facet and be reflected back into a region defined by the ridge. The light is coupled into the broad area planar optical waveguide on either side and is therefore much less likely to be reflected back towards the ridge and be coupled efficiently into a mode guided by it.

The structure of the device according to the first aspect of the present invention is particularly applicable to a superluminescent diode (SLD), where it is important to achieve good effective end facet anti-reflectivity and thereby suppress unwanted Fabry Perot oscillation.

Preferably, the optical device comprises a superluminescent diode (SLD).

Of course, the optical device may equally well be another form of planar ridge waveguide device which requires low effective reflectivity towards a facet. Such devices include laser devices, which need to operate at high power while maintaining good single mode operation.

Alternatively, therefore, it is preferred that the optical device comprises a distributed feedback (DFB) laser.

Preferably, the ridge meets the facet at substantially 90°.

Light guided by the presence of the ridge and that is incident normally on the facet will tend to emerge with a more symmetric profile, thereby facilitating coupling of the light into other devices including an optical fiber.

Preferably, both trenches have a tapered region.

A tapered region on either side of the ridge will cause light to couple out on both sides thereby dispersing it further. It will also tend to result in a more symmetric guided mode propagating towards the facet.

Preferably, a portion of the ridge is curved.

If a portion of the ridge is curved, any light propagating away from the facet that has not been coupled out from the region beneath the ridge will emerge into the broad area waveguide in a direction that is unlikely to be at normal incidence to another facet of the optical device. This further reduces the likelihood of reflected light being coupled back into a mode guided by the ridge.

Preferably, the curved portion is defined by a smooth function that may also be monotonic. Alternatively, the curved portion may comprise one or more straight sections, so as to be defined in a discrete manner.

A smooth curved portion will facilitate a gradual adiabatic coupling of light from the region confined by the ridge whilst also promoting a more symmetrical mode propagating toward the output facet.

Preferably, the curved portion of the ridge is defined by the tapered region of a trench.

In this way both the loss by evanescent coupling and the change in the propagation direction of the remaining guiding light occurs simultaneously. The desired structure can be achieved by defining the trenches in a single fabrication process.

Preferably, the width of the ridge is substantially constant along its length. A constant ridge width can help to promote a better defined mode.

Preferably, the two trenches have substantially the same length as the ridge.

Equal lengths ensure that the ridge terminates by opening out into the broad area waveguide in a symmetrical manner. Although, if the ridge is curved, the outer wall of one trench will of course be slightly longer than the outer wall of the other trench.

Preferably, a trench is filled. More preferably, a trench is filled with a material selected from a group which includes a dielectric material, polyimide, benzocyclobutene and a III-V semiconductor material.

By filling both trenches a buried structure can be achieved, which both protects the side walls of the ridge and also allows the refractive index of the material surrounding the ridge to be determined by appropriate choice of material.

The reflectivity of the output facet may also be tailored by the application of a suitable thin film coating.

Preferably, the facet is anti-reflection coated.

If the optical device comprises an active device, it will typically have an active region providing optical gain.

Preferably, the optical device further comprising an active region located beneath at least a portion of the ridge. The active region may be quantum well intermixed to tune the band gap in the active region to the desired wavelength.

Preferably, at least one of the trenches extends down to at least the active region in order to achieve suitable optical confinement.

It is further preferred that the optical device comprises an absorbing region. An absorbing region located some distance away from the facet provides another loss mechanism for radiation propagating away from the facet. Preferably, the absorbing region is located in the broad area waveguide into which light guided by the ridge emerges.

Furthermore, by reverse biasing at least a portion of the absorbing region via a suitably located electrode, the region can act as a photodetector, generating a photocurrent related the optical signal strength. Such a photodetector can act as an integrated monitor for the optical device and may be used to provide a feedback signal.

According to a second aspect of the present invention a method for reducing reflections in an optical device comprising a planar optical waveguide having a ridge comprising the step of:

providing two trenches which extend from a facet of the planar optical waveguide to define the ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

According to a third aspect of the present invention a method for fabricating an optical device comprising the steps of:

providing a planar optical waveguide on a substrate;

etching at least two trenches in the planar optical waveguide which extend from a facet of the waveguide to define a ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

Preferably, the optical device in the second and third aspects of the present invention comprises a superluminescent diode (SLD).

Brief Description of the Drawings

Examples of the present invention will now be described in detail with reference to the drawings in which:

Figure 1 shows the structure of a prior art non-excitation absorption SLD;

Figure 2 shows the structure of a prior art SLD with straight portion and bending portion at the end facet;

Figure 3 shows (a) a plan view and (b) a cross section view of the structure of a prior art non-excitation absorption SLD with a bend waveguide and tapered end;

Figure 4 shows (a) a 3D view and (b) a plan view of the structure of an SLD according to the present invention;

Figure 5 shows (a) a 3D view and (b) a plan view of the structure of another SLD according to the present invention;

Figure 6 shows the exemplary x-z dimensions of an SLD of the type shown in Figure 5.

Figure 7 shows a simulation of the x-z optical field distribution in the device of Figure 6;

Figure 8 shows an x cross section through the optical field distribution of Figure 7 at approximately z=280μm;

Figure 9 shows the measured light-current characteristics of an SLD of the type shown in Figure 5;

Figure 10 shows the output spectrum of the SLD characterised in Figure 9;

Figure 11 shows the structure of an SLD according to the present invention with an active region and an absorption region; and,

Figure 12 shows the structure of an SLD according to the present invention with an active region, an isolation region and monitoring photodiode region.

Detailed Description

Some prior art approaches to solving the problem of unwanted reflections in an SLD are illustrated in Figures 1 to 3. Figure 1 shows a prior art SLD of the type which employs a non-excitation absorption region to reduce backward propagating light. Figure 2 shows a prior art SLD which employs a straight portion and a bend portion. The bend portion extends to the facet such that the waveguide meets the facet at an angle with a corresponding low reflectivity. Finally, Figure 3 illustrates a prior art technique, based on a buried heterostructure stripe, which employs a bend waveguide with a tapered end to suppress unwanted lasing oscillation. However, although the above designs provide improved SLD performance, each technique has its drawbacks or limitations.

Figure 4 illustrates a typical SLD 40 according to the present invention. The device structure consists of a ridge 41 defined by two etched trenches 42 located on either side. The ridge waveguide 41 converges into a slab waveguide 44 at the desired anti-reflection end of the device. More importantly, the widths of the trenches on both sides are reduced 43 as the ridge waveguide 41 is led towards the rear facet 46. The waveguide 41 is formed so as to meet the light output front facet 45 at 90°. In this design, the optical mode profile will be symmetrical about its propagating axis, hence leading to easier and more efficient coupling to an optical fiber. Output light emerging normal to the end facet does not suffer from beam direction drift with intensity, which is often observed in bend and tilted waveguides. However, if so desired, the waveguide 41at the light output front facet 45 can also be formed tilted at an angle to the facet.

In this design, back reflection from the non-output facet 46 is greatly reduced by introducing loss for light propagating in the direction away from the output facet inside the ridge waveguide 41 through controlled mode coupling between the ridge

waveguide 41 and the slab waveguides 44 beyond the etched trenches 42. The mode coupling is achieved via tapered trenches 43 with the width of a trench reducing in the propagation direction away from the output facet. The resulting enhanced mode coupling will lead to the light propagating along the ridge waveguide 41 in the direction away from the output facet 45 being gradually guided out into the outer slab waveguides 44 beyond the etched trenches 43. Consequently, the amount of light reaching the rear facet 46 is minimised, resulting in the amount of light that is reflected back to the ridge waveguide 41 being drastically reduced.

Away from the front facet 45, the ridge waveguide region 41 converges into the rear slab region 44 before reaching the end facet. Upon entering this free-propagating slab region, the lateral field enlarges into the slab due to the lack of lateral optical confinement. Any back-reflected field returning from the rear facet 46 is propagating in an enlarged mode, which is highly mismatched with the guided mode of the ridge waveguide 41, thus reducing the amount of light propagating back into the ridge waveguide 41.

In order to further reduce the residual back reflection, the ridge waveguide 51 may be bent or curved with a small bending radius. The width of the side trenches 52 may be reduced concurrently 53. Figure 5 shows an example of this embodiment of the present invention. The curved ridge 57, in combination with the tapering trench 53, results in most of the light that is propagating in the ridge waveguide 51 towards the rear facet 56 being coupled out of the guiding region 57 into the outer slab waveguides 54 beyond the trenches. This mechanism also results in the remaining guided light exiting at an angle into the back slab 54, further reducing the reflection arising from the ridge and back slab waveguide interface. The tapered trench 53 also functions to diffract light coming back from the rear facet 56 away from the waveguiding region 51.

This device configuration of a ridge waveguide with tapering side trenches enables the reflection of light from the rear facet to be reduced immensely. For a superluminescent diode, this device structure helps enhance the superluminescent effect, whereby the diode operates without lasing with high power emission. An anti-reflection coating can be applied to the light emission facet in order to further enhance the superluminescent performance.

Figure 6 illustrates the typical dimensions that may be employed in a device of the type shown in Figure 5. As indicated, the trenches begin with a width of 11 μm

reducing to 1 μm over a longitudinal distance of 300 μm. Figure 7 shows the results of a simulation of the optical field distribution in the device of Figure 6. It can be seen that the field radiates out of the ridge waveguide region as the trenches taper in with the bending ridge. Upon exiting the waveguide, the field spreads out rapidly and asymmetrically. The field is incident on the rear facet at an angle and some distance away from the ridge. Figure 8 shows a cross section through the simulated results of Figure 7 at a position near to the exit of the ridge waveguide. The graph shows the detailed distribution of the optical field in the transverse (x) direction at a longitudinal (z) position of approximately 280μm. It can be seen that a significant portion of power is being steered into the radiation modes of the outer slab regions beyond the etched trenches.

The epitaxial structure of the SLD can be implemented using conventional technology such as metal organic chemical vapour deposition (MOCVD) or molecular beam epitaxy (MBE). The devices are fabricated from a semiconductor material, such as GaAs/AlGaAs and InGaAsP/InP, which permits the introduction of heterostructures and/or quantum well structures. The ridge waveguide may be etched down to the active region (a normal ridge structure) or beyond the active region to form a high mesa structure for enhanced optical confinement. The etched trenches on the sides of the ridge waveguide may also be filled using a dielectric material (i.e. silicon nitride or silicon dioxide), polyimide, benzocyclobutene (BCB), or III-V semiconductor material, thus forming a buried structure.

Figure 9 shows the light output power versus current injection measured at 25 °C for a submounted SLD fabricated according to the proposed design, with tapering side trenches and curved ridge waveguide. A power level of more than 8 mW is achieved with an injection current of 300 mA. The corresponding spectrum measured with an optical spectrum analyzer (OSA) is shown in Figure 10. A spectral width, measured by the full-width at half-maximum (FWHM), of larger than 40 nm can be obtained at varying levels of current injection.

In order to further enhance the superluminescent effect and enlarge the spectral width, the bend waveguide region can be made to be absorptive, as shown in Figure 11. In the conventional approach, the integration of an active region and an absorbing region usually involves many steps of etching and regrowth. This results in low yields and also a mismatch in the optical propagation coefficient at the interfaces with the regrown material, leading to back reflections. An exemplary

embodiment of a typical method to obtain higher bandgap energy in the active region is to use the quantum well intermixing (QWI) technique. The use of this method improves this situation considerably as it provides a gradual and very small change in the refractive index at the interfaces. Therefore, back reflection from the interface can be suppressed, and the unwanted Fabry-Perot modes of oscillation can be eliminated.

Moreover, the proposed configuration also allows for easy integration of a photodiode for monitoring the SLD optical output. A monitoring photodiode can be implemented by adding a metal contact to the absorption region and an isolation groove between the absorption and active gain regions, as shown in Figure 12. By reverse biasing the absorption region, an integrated photodiode is obtained which yields a photocurrent signal that is proportional to the light being emitted by the SLD. This embodiment of the present invention ensures that all light propagating towards the bend waveguide will be completely absorbed, effectively rendering the back facet completely anti-reflecting.

In addition to enhancing greatly the performance of superluminescent diodes, the tapered trench structure can also be incorporated in other types of optical device such as the distributed feedback (DFB) laser. The low reflectivity structure can help to eliminate the undesirable Fabry-Perot (FP) reflections within the DFB laser, which tend to degrade the single mode operation of the laser. It is expected that such a design would permit very high power single-mode output.

In conclusion, the tapered side trench structure employed in an optical device according to the present invention provides an effective power dump, whereby undesired optical power is coupled out of the confining optical waveguide to slab waveguides located on either side. These broad area slab waveguides provide no lateral confinement and so light is quickly dispersed with very minimal possibility of back coupling into the original optical waveguide. The mismatch in mode size helps to minimise back coupling of any reflected radiation. The use of an angled or curved waveguide can further reduce the likelihood of back coupling. Consequently, very effective anti-reflection and suppression of backward propagation can be realized. The structure is particularly well suited to a high performance superluminescent diode, but may also be employed in other types of optical device where low effective reflectivity is required.

CLAIMS

1. An optical device comprising a planar optical waveguide having two trenches which extend from a facet of the planar optical waveguide, the two trenches defining a ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

2. An optical device according to claim 1, wherein the optical device comprises a superluminescent diode (SLD).

3. An optical device according to claim 1, wherein the optical device comprises a distributed feedback (DFB) laser.

4. An optical device according to any preceding claim , wherein the ridge meets the facet at substantially 90°.

5. An optical device according to any preceding claim , wherein both trenches have a tapered region.

6. An optical device according to any preceding claim, wherein a portion of the ridge is curved.

7. An optical device according to claim 6, wherein the curved portion comprises at least one straight section.

8. An optical device according to claim 6 or 7, wherein the curved portion of the ridge is defined by the tapered region of a trench.

9. An optical device according to any preceding claim, wherein the width of the ridge is substantially constant along its length.

10. An optical device according to any preceding claim, in which the two trenches have substantially the same length as the ridge.

11. An optical device according to any preceding claim, wherein a trench is filled.

12. An optical device according to claim 11, wherein a trench is filled with a material selected from a group which includes a dielectric material, polyimide, benzocyclobutene and a III-V semiconductor material.

13. An optical device according to any preceding claim, wherein the facet is anti-reflection coated.

14. An optical device according to any preceding claim, further comprising an active region located beneath at least a portion of the ridge.

15. An optical device according to claim 14, wherein at least one of the trenches extends down to at least the active region.

16. An optical device according to claims 14 or 15, wherein the active region is quantum well intermixed.

17. An optical device according to any preceding claim, further comprising an absorbing region.

18. An optical device according to claim 17, wherein at least a portion of the absorbing region is reverse biased to act as a photodetector.

19. A method for reducing reflections in an optical device comprising a planar optical waveguide having a ridge comprising the step of:

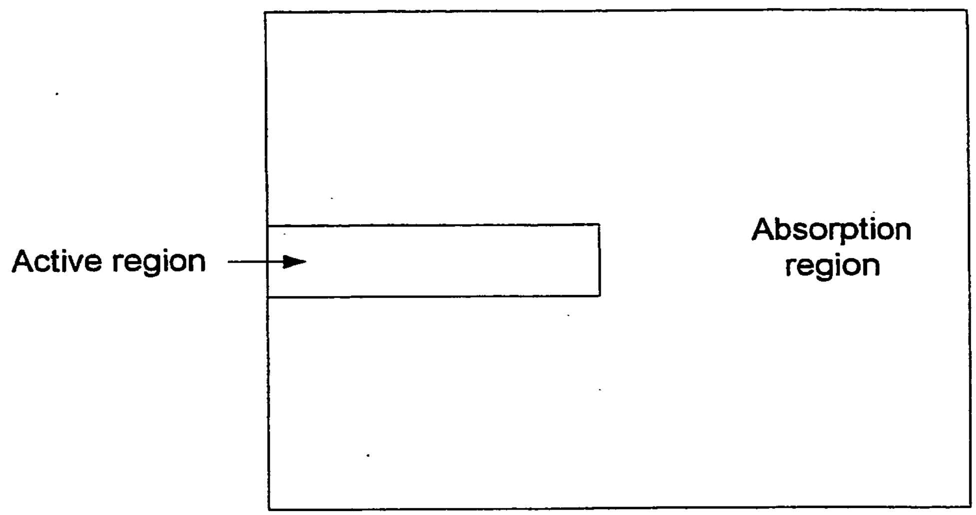
providing two trenches which extend from a facet of the planar optical waveguide to define the ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

20. A method for fabricating an optical device comprising the steps of:

providing a planar optical waveguide on a substrate;

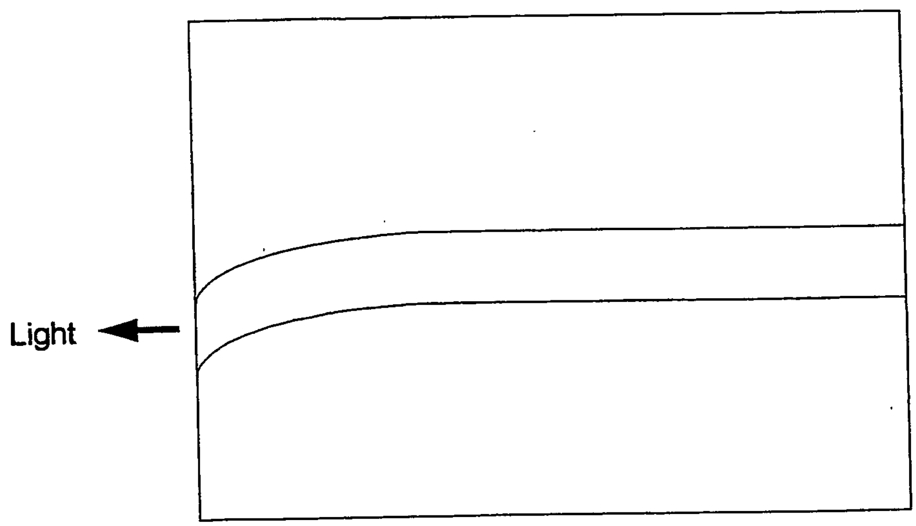
etching at least two trenches in the planar optical waveguide which extend from a facet of the waveguide to define a ridge therebetween in the planar optical waveguide, at least one trench having at least a region which is tapered, wherein the width of the trench decreases with distance from the facet measured along the length of the trench.

21. A method according to claim 19 or 20, in which the optical device comprises a superluminescent diode (SLD).



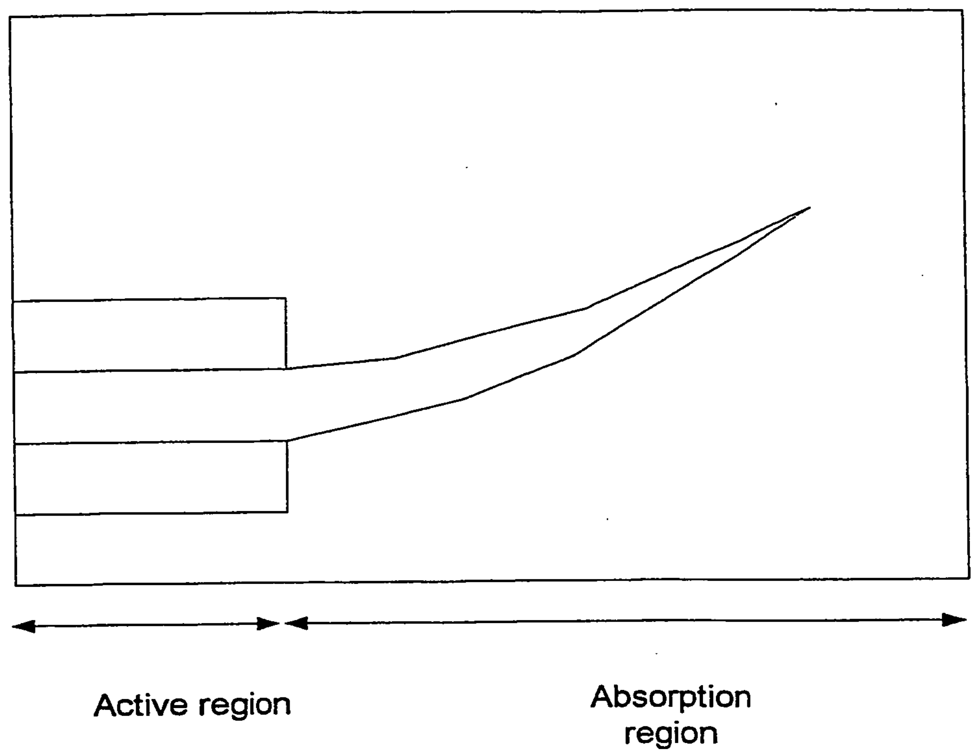
PRIOR ART

Figure 1



PRIOR ART

Figure 2



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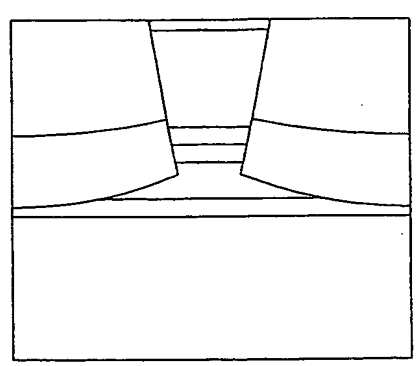

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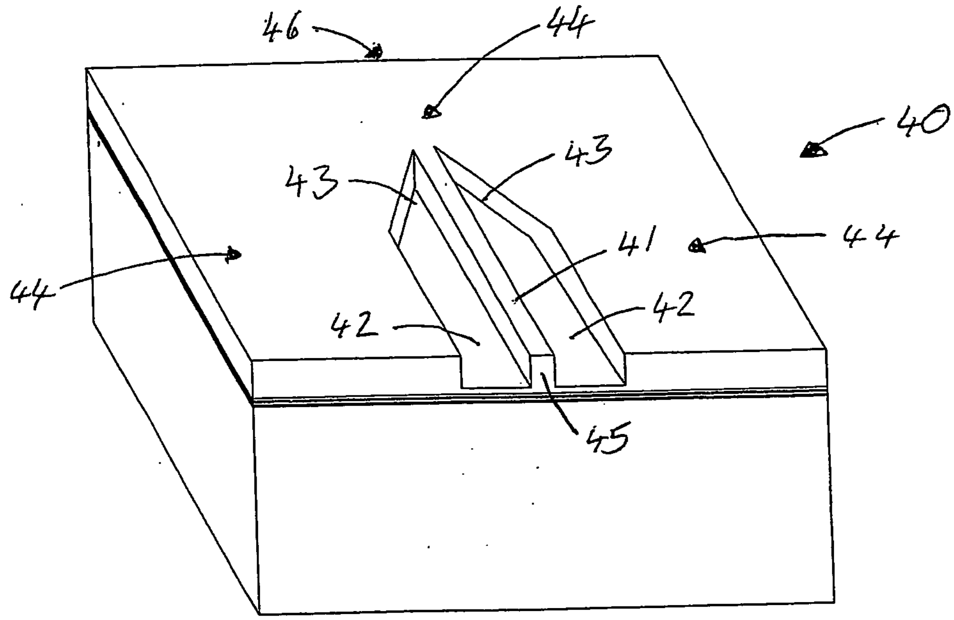
PRIOR ART

Figure 3



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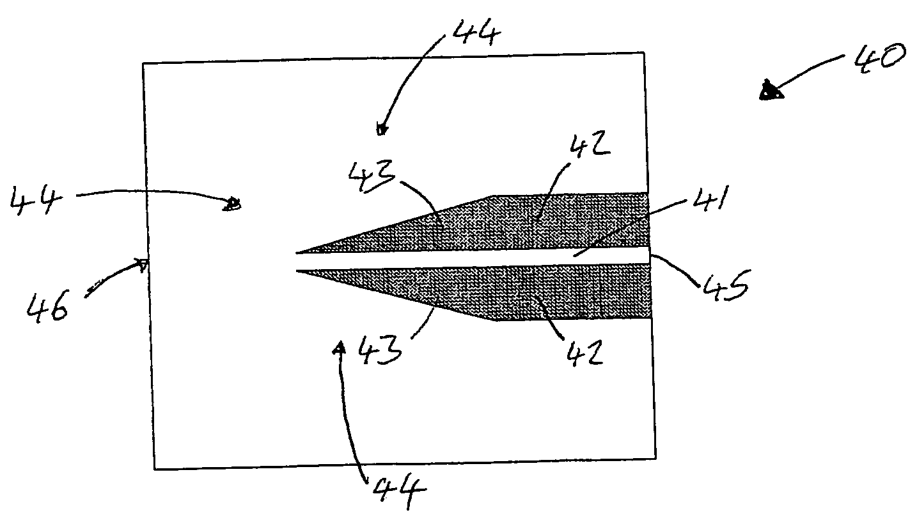

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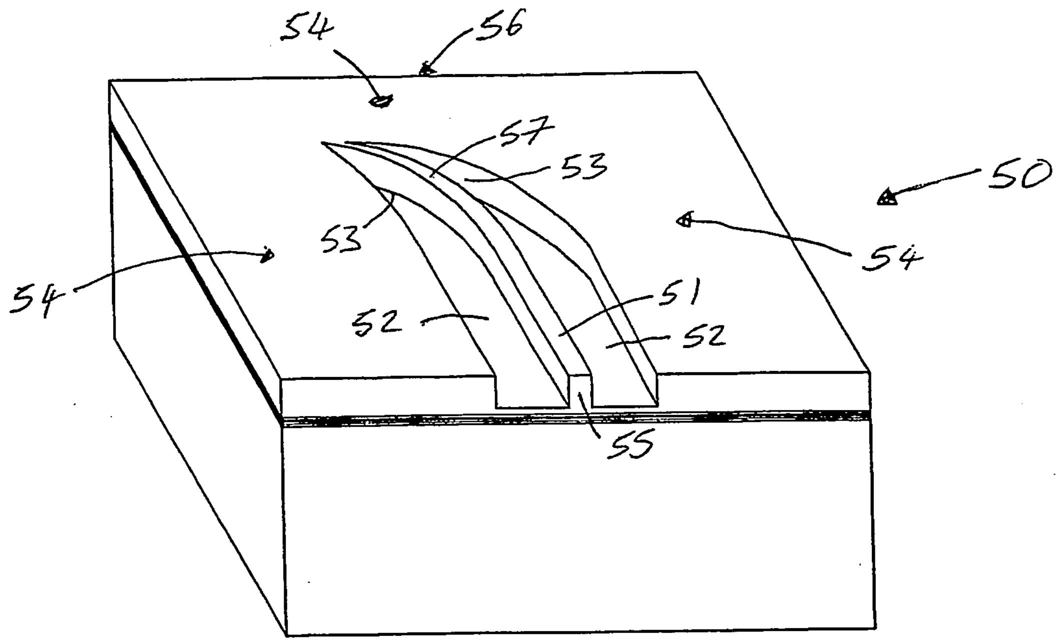
Figure 4



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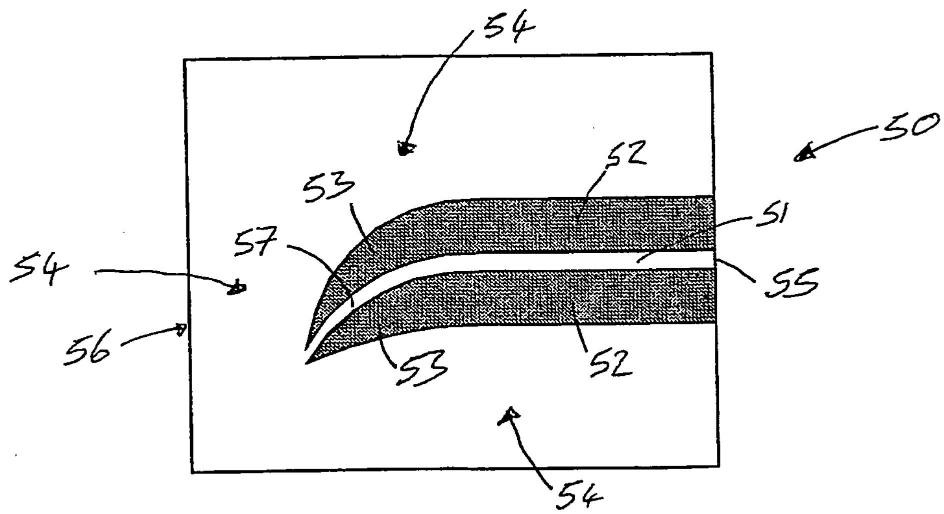

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Figure 5

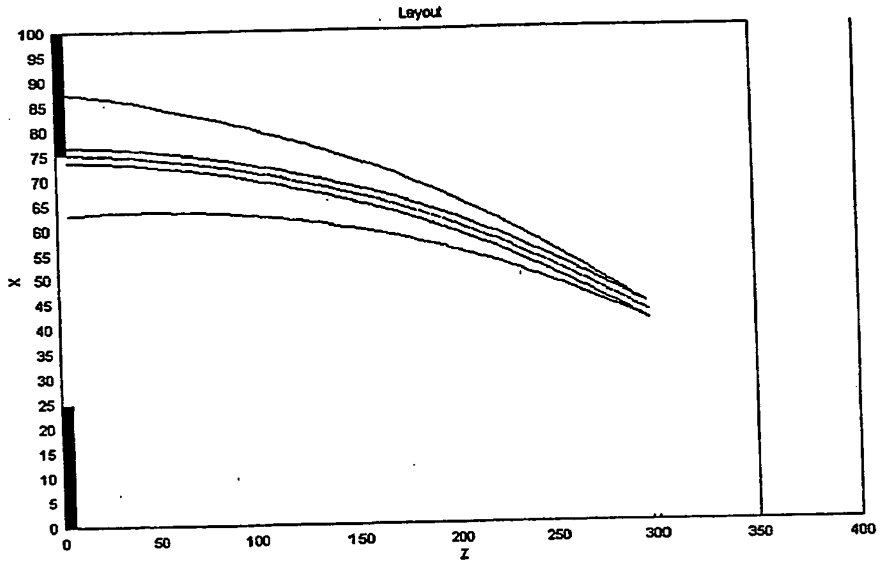

Figure 6

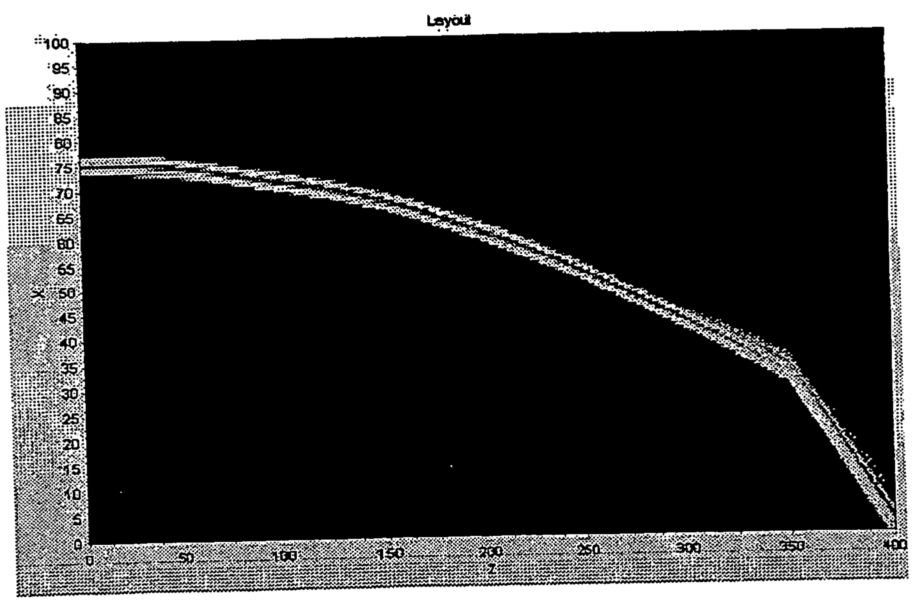

Figure 7

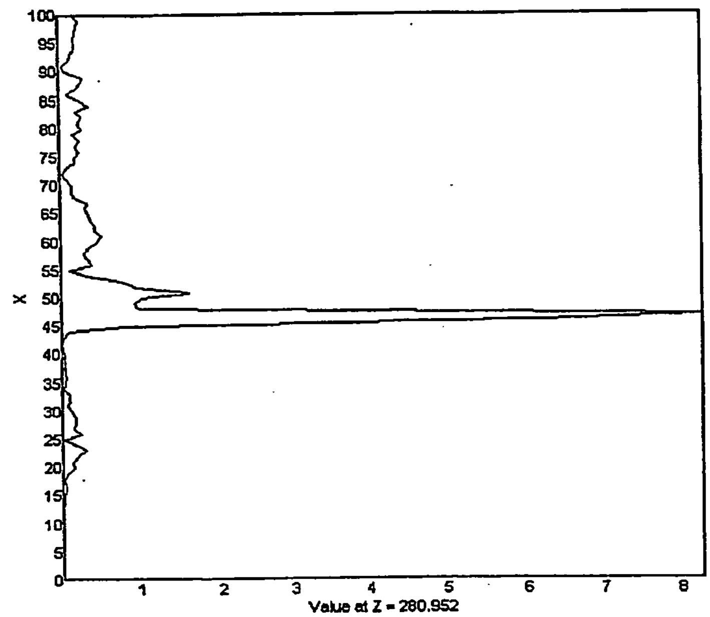
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Figure 8

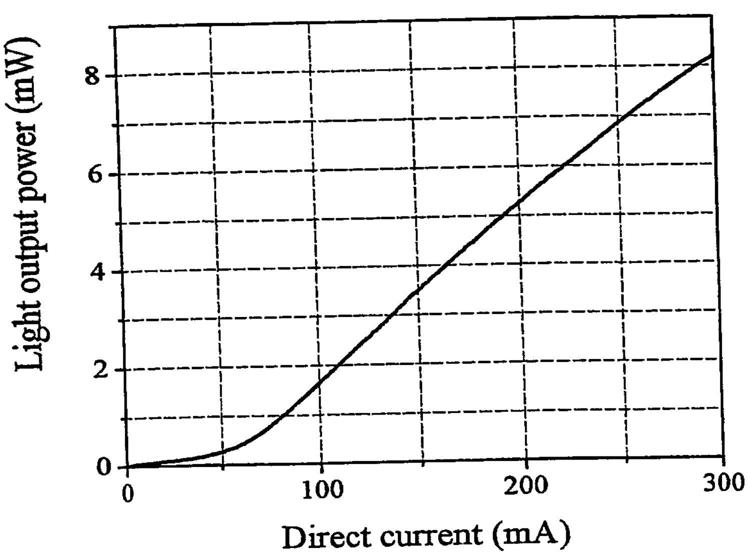
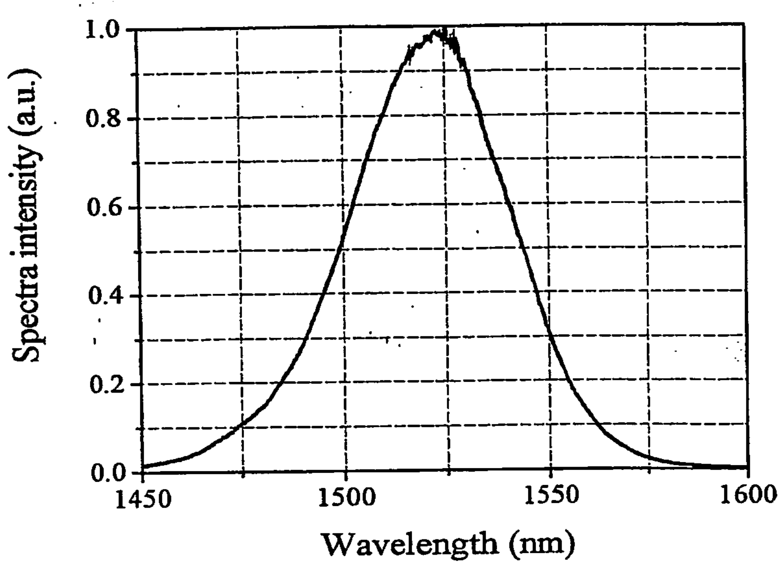


Figure 9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0.4
0.2
0.0
Spectra intensity (a.u.)
1450
1500
1550
1600
Wavelength (nm)

Figure 10

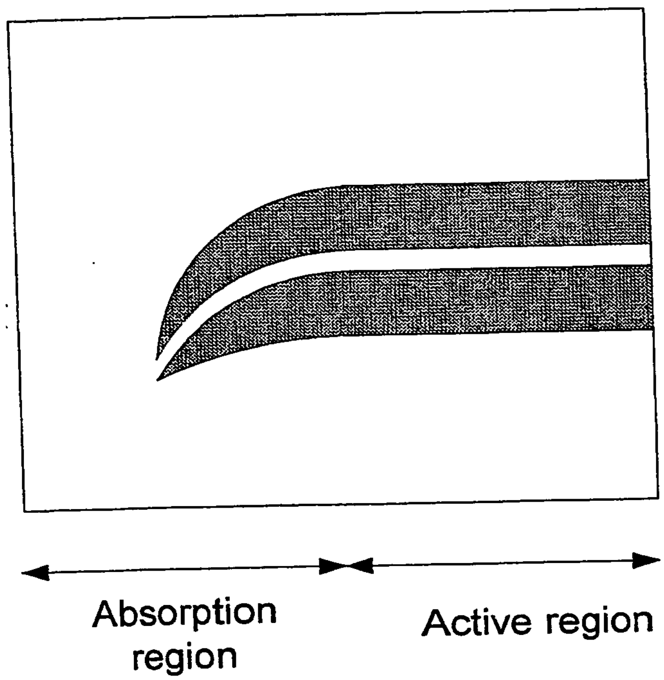

Figure 11

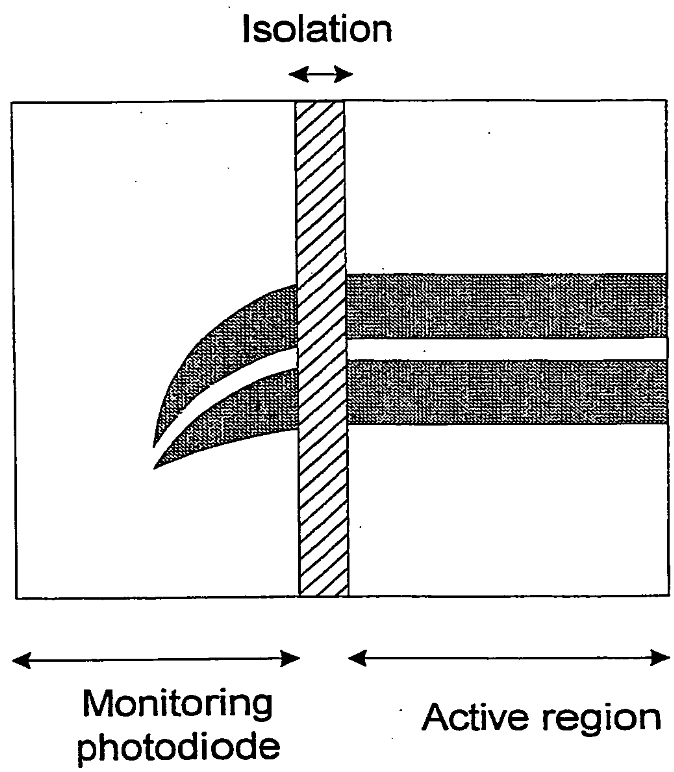

Figure 12

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 03/02912

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/12 H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 689 358 A (YOKOYAMA KIYOYUKI ET AL) 18 November 1997 (1997-11-18)	1-5, 11-15, 17,19-21
Y	column 20, line 13-64 column 27, line 42 -column 28, line 48 column 37, line 16 -column 19, line 14; figures 5,6,19,20,41-46 ---	18
X	WO 01 57565 A (AITCHISON JAMES STEWART ;QUI BO CANG (GB); MARSH JOHN HAIG (GB); U) 9 August 2001 (2001-08-09) page 2, line 5 -page 9, line 35; figures 1,2 ---	1,5-8, 10,13, 14,16, 17,19,20

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 November 2003	20/11/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Wolf, S

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Internat[redacted] Application No
PCT/GB 03/02912

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	US 5 252 839 A (FOUQUET JULIE E) 12 October 1993 (1993-10-12) column 2, line 29 -column 8, line 56; figures 2,5,15	18
A	PATENT ABSTRACTS OF JAPAN vol. 1998, no. 05, 30 April 1998 (1998-04-30) & JP 10 026710 A (HITACHI LTD), 27 January 1998 (1998-01-27) abstract	11,12
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A	MAGARI K ET AL: "HIGH EFFICIENCY 1.3 um SUPERLUMINESCENT DIODE WITH ABSORBING TAPERED WAVEGUIDE" ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 26, no. 18, 30 August 1990 (1990-08-30), pages 1445-1446, XP000108551 ISSN: 0013-5194 the whole document	1,2,13, 17,19-21
A	US 4 999 686 A (AUTIER PHILIPPE ET AL) 12 March 1991 (1991-03-12) column 3, line 60 -column 6, line 44; figures 2-5	1,6,19, 20

INTERNATIONAL SEARCH REPORT

Information on patent family members

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